

Use spread-spectrum techniques to reduce EMI

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EMI is a major concern in PC design, because it determines whether a system or PC motherboard gets approved for sale by the US Department of Commerce. This situation is especially true in designs that feature Pentium-class processors, high-speed buses, and several clock outputs. EMI testing occurs late in the design process, so failing the test can mean expensive redesign and increased time to market. In addition to material costs, using shielding as a way to reduce EMI significantly increases production complications, further driving up system cost.

An alternative approach is to control EMI by eliminating

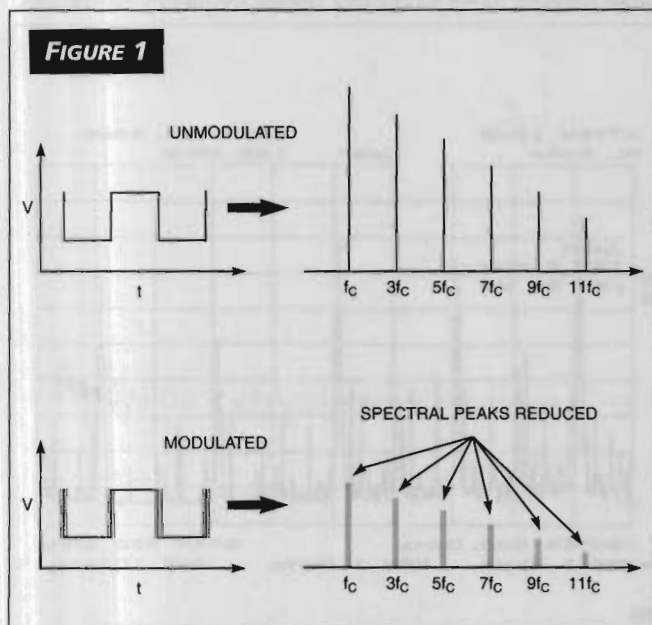
In many countries, EMI requirements limit the selling of PCs. Spread-spectrum techniques are cost-effective ways to control clock-generated EM emissions.

rather than merely containing it. One expensive and time-consuming way to achieve this goal is to redesign a system specifically to reduce emissions once you determine its EMI levels. A more efficient and

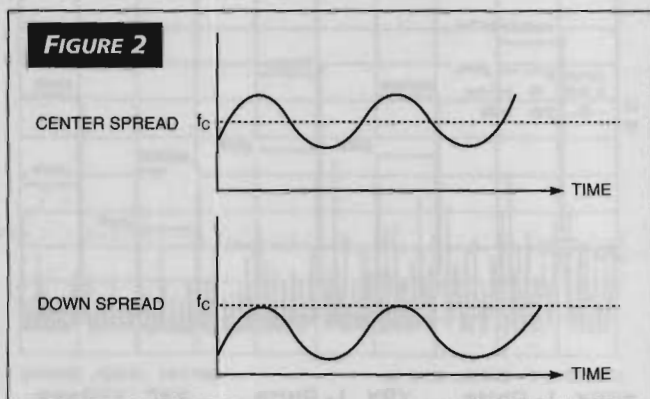
cost-effective alternative is to control clock emissions, a major source of EMI.

Harmonics and multiple lines create the problem

EMI is a growing problem in today's computers because they operate faster, which requires shorter rise times for square-wave clock signals. Also, system motherboards have more clocked elements, resulting in more lines to radiate energy. For example, in a 486-based system with a 66.6-MHz bus, the rise times are typically 2 nsec. Generating a square wave with this rise time does not produce a large number of higher order harmonics. Furthermore, the system most likely uses extended-data-out (EDO) DRAM, which has its own



Slight modulation of a clock spreads the energy of the fundamental frequency, minimizing fundamental and harmonic-frequency energy peaks. This technique reduces system EMI.



Center-spread modulation shifts the carrier frequency above and below the original fundamental frequency. Down-spread modulation shifts the carrier frequency down by half the modulation amount, so that the modulated waveform is centered on a new carrier.

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clocking scheme and is not operating at a 66.6-MHz clock rate. As a result, a limited number of lines radiate a relatively low level of harmonic-content energy, so traditional EMI shielding practices are adequate.

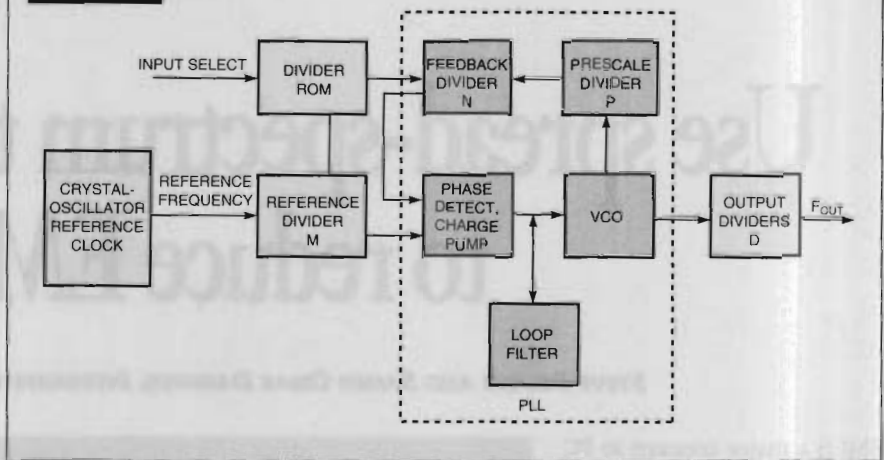
In a Pentium-based system, clock rise times are approximately 800 psec, even with a 66.6-MHz host clock. To generate a square wave with such a rise time, you create much greater higher-order harmonic content, which contains a high energy level. With a clock frequency of 100 MHz, the problem becomes worse because the harmonics are at much higher frequencies and contain even more energy.

In addition, the Pentium system most likely uses synchronous DRAM (SDRAM), so every slot has four clocks. A high-end computer has four slots, 16 memory-clock lines, and four lines for the CPU. Thus, numerous lines radiate large amounts of energy. Because the outputs are synchronous, the system simultaneously switches all 16 lines, causing a large energy spike and generating excessive spectral energy.

Alternatives to shielding

Pulse shaping, slew-rate control, staggered outputs, and spread-spectrum techniques can reduce clocking-related EMI. Of these, spread spectrum is the easiest to implement and the most efficient. Spread spectrum slightly modulates a clock signal's frequency, spreading the energy of the funda-

FIGURE 3

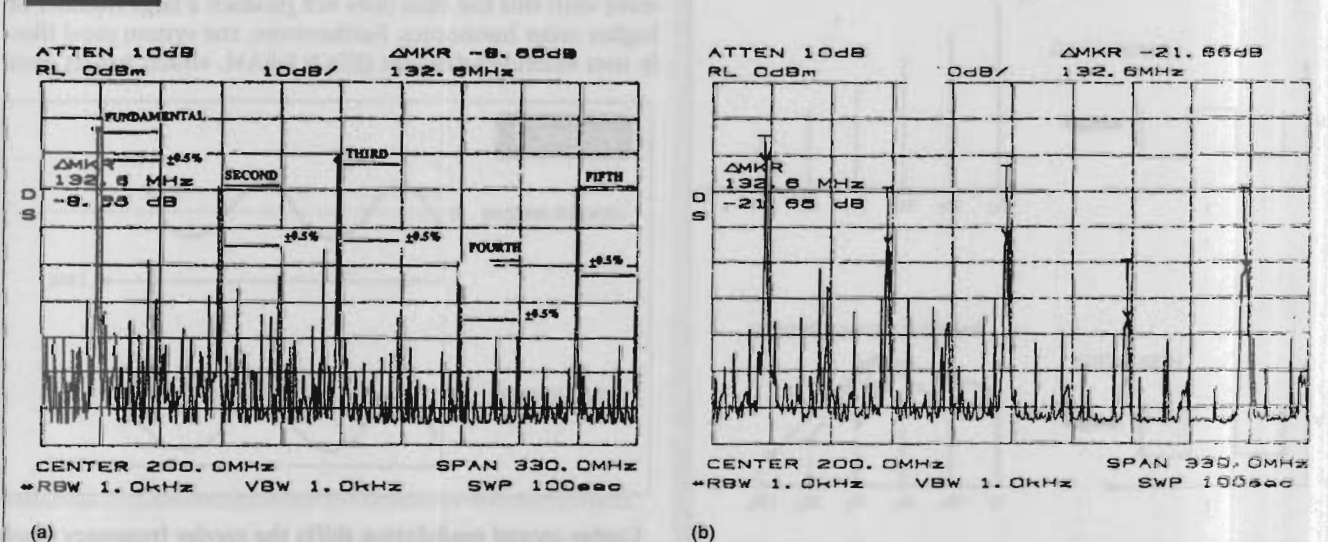


Modulating the input of the VCO in a closed loop is an accurate and predictable way to use a spread-spectrum technique for reducing clock EMI.

mental frequency to minimize any energy peaking at specific frequencies (Figure 1). This approach reduces the fundamental-clock-frequency EMI, as well as the higher frequency harmonic components, reducing total system-EMI radiation. By reducing its spectrum-peak amplitude, a system more easily and more cheaply meets the standards of electromagnetic-compatibility (EMC) tests than do other EMI-containment techniques.

One technique designers use to reduce EMI is pulse shaping, which requires control of the output waveshape. You use pulse shaping to try to control higher frequency harmonics.

FIGURE 4



This wide-view spectrum plot of 66.6-MHz-fundamental to fifth-harmonic frequencies shows a normal spectrum (a) and the energy reductions achieved with a $\pm 0.5\%$ (0 to -1%) down-spread shift of the fundamental frequency (b).

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Pulse shaping does not control the spectral energy of the fundamental but changes the shape of the rising edge, rounding off the corners and reducing some of the higher frequency components and their energy. Pulse shaping works if you can control the portion of the waveform near the switching threshold.

Unfortunately, pulse shaping makes for a difficult balancing act between too much rounding, which can begin to look like more of an analog function, and not enough rounding to achieve the desired EMI reduction. In addition, process, temperature, and voltage variations disrupt the balance. The techniques you use to obtain optimum rounding may not give consistent results from run to run in manufacturing. For example, carefully set capacitive or resistive shaping values change from production lot to production lot. As a result, you must overdesign the system to ensure that process variations leave sufficient EMI control and rise time.

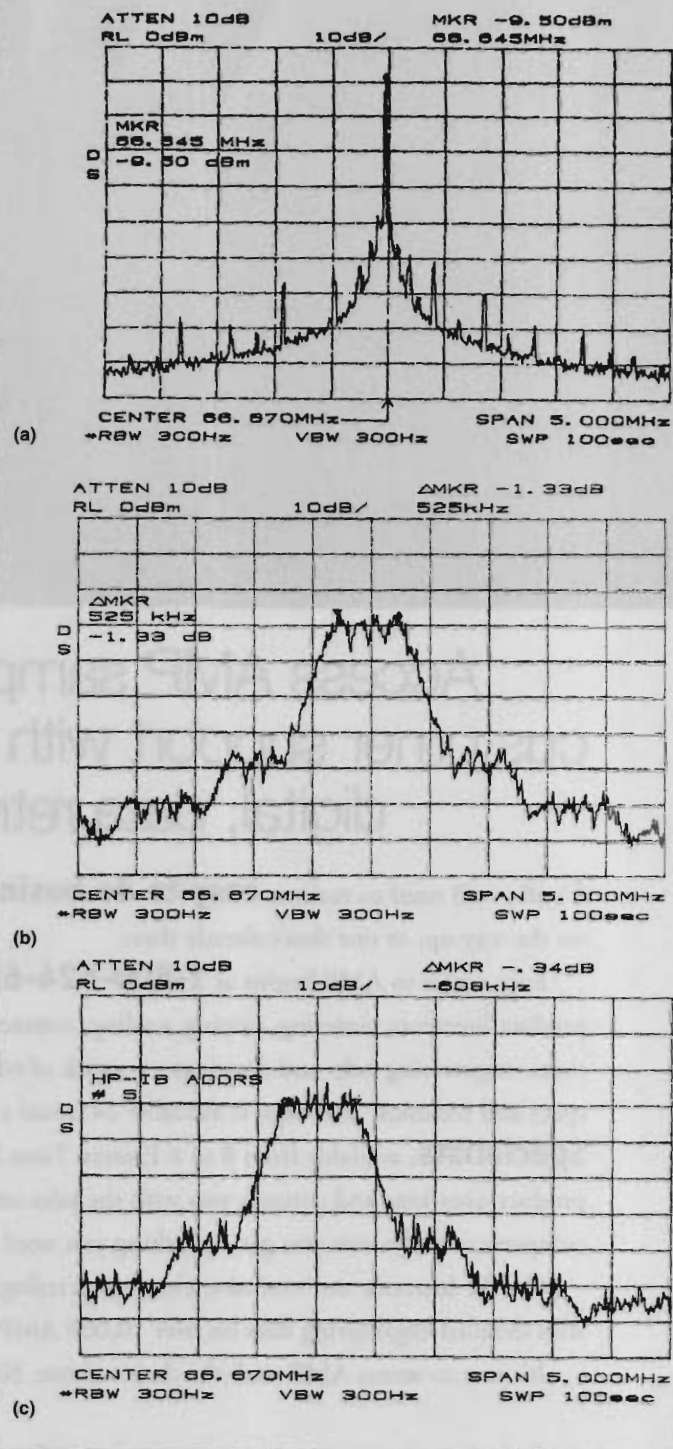
Also, pulse shaping changes only the higher order harmonics and not the fundamental frequency. Supposedly, enough room is available under the peak-power level that the fundamental does not exceed allowable tolerances. This assumption may not be true, particularly in light of changing FCC regulations.

Another approach to reducing EMI, slew-rate control, manages the rising-edge slope by maintaining an output drive that doesn't overcharge load capacitance. Slew-rate control achieves this maintenance by creating a current-controlled output that avoids having a fast, high current and should theoretically be effective. However, as with pulse shaping, a major issue is how well you can maintain that control on a manufacturing lot-to-lot basis and across various voltage and temperature ranges. The design must account for the worst-case process and for both high and low temperatures and voltages. These potential variations are both critical and unpredictable. As a result, slew-rate control is difficult to implement and unreliable.

Another alternative is staggering the outputs in a system using SDRAMs. As noted before, a high-end system typically has 16 memory lines, all of which theoretically switch at once. In practice, you cannot achieve absolute synchronous switching, so design specifications allow a 250-psec window within which the system must switch all the lines. For example, the system can set one group of lines 110 psec early; another, 30 psec early; a third, 30 psec late; and a fourth, 110 psec late. This approach would temporally spread the energy. The frequencies remain the same, but they're phase-shifted, decreasing the energy that appears at any instant and reducing EMI.

A major drawback of output staggering is that output-to-output and tolerance-related variations are inherent and might by themselves occupy the time window. So, although output staggering is theoretically good, maintaining target control over manufacturing, voltage, and temperature variations can be diffi-

FIGURE 5



A magnified spectrum plot of a 66.6-MHz fundamental frequency shows the energy present in a normal spectrum (a), a spectrum with a center-spread shift of $\pm 0.5\%$ (b), and a down-spread shift of $\pm 0.5\%$ (c).

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cult and make this technique unacceptable.

Another approach, spread spectrum, spreads the energy of a fundamental frequency to minimize any peaking of energy at specific frequencies. This technique reduces both the fundamental-frequency EMI and the higher frequency harmonic components, significantly reducing overall system EMI radiation without compromising clock-edge rise and fall times. With lower spectrum-peak amplitudes, a system meets and has more margin for EMC. Spread spectrum is the simplest, most efficient technique and offers the most immunity to manufacturing-process variations.

Spread-spectrum basics

In measuring EMI to determine regulatory compliance, the FCC samples the spectrum a system emits. Basically, someone sweeps a spectrum analyzer across a frequency range to look for energy peaks that exceed a limit. If the energy from a fundamental peak spreads to a band plus or minus some percentage on either side using a controlled shift pattern, the energy is lower at any frequency. The same energy still exists but is now spread across a controlled range of frequencies. Spreading the spectrum lowers the fundamental-frequency energy because the clock spends part of its time at a lower frequency and part at a higher frequency. Despite the energy spread, the clock is still a square wave.

For example, you might modulate a 66.6-MHz clock frequency by 1%. The period for a 66.6-MHz clock is 15 nsec, so a 1% modulation would be 150 psec; the period would move 75 psec on either side of 15 nsec in a controlled manner. Engineers design the system to respond with a clock that has some variation, because it must accommodate inherent random variations. Because you design the system for clock variations, slowly varying the clock does not affect system operation.

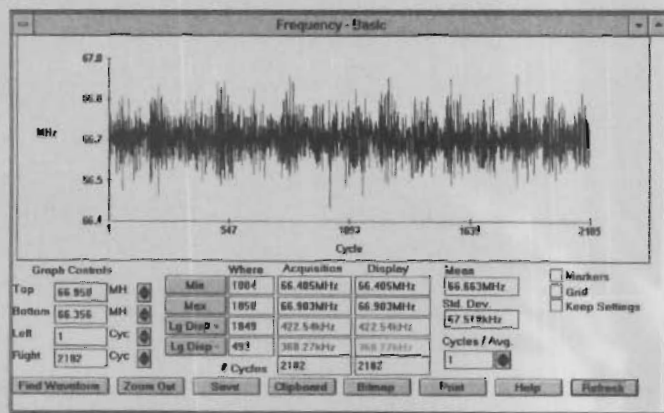
Modulation amount and rate

The amount and rate of fundamental-frequency modulation are two of the first decisions you must make when implementing a spread-spectrum design. You base both decisions on practical considerations. For example, experience shows that a spread of 0.5% sufficiently reduces EMI and remains close to the clock frequency, which means less tracking variation.

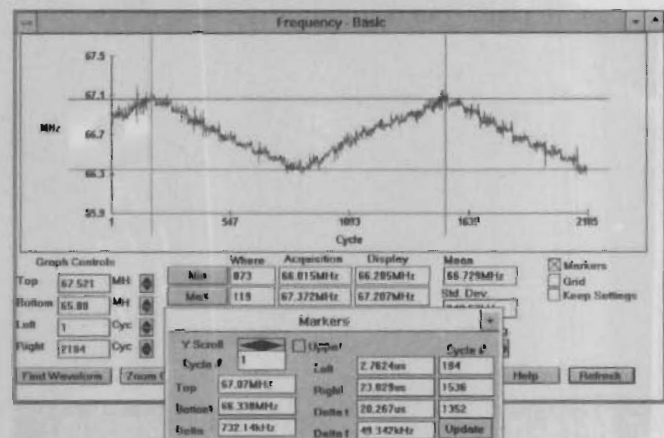
Similarly, modulation-rate selection involves a number of empirical considerations. For its spread-spectrum-enabled clock chips, Integrated Circuit Systems (ICS, www.icst.com) uses a 50-kHz modulation rate. ICS chose this rate because it is higher than the normal audio frequency, eliminating the chance of a user's hearing a high-pitched squeal from the system. ICS also chose the rate for compatibility with the chip set and CPU, both of which have PLLs that operate with a loop bandwidth of greater than 1 MHz.

The most important design decision is whether to use center- or down-spread modulation (Figure 2). Center-spread modulation shifts the frequency above

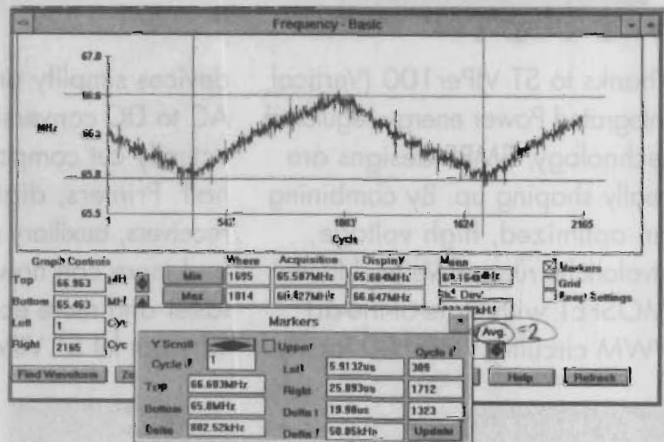
FIGURE 6



(a)



(b)



(c)

As these frequency-versus-cycle-number diagrams show, you can significantly reduce the spectral energy in a normal spectrum (a) with $\pm 0.5\%$ center-spread shifting (b) and down-spread shifting (c).

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and below the original fundamental frequency. The advantage of this modulation is that average system frequency is always the same. The system always sees a 66.6-MHz clock as a 66.6-MHz clock, so performance does not degrade from board to board.

The major disadvantage of center spreading is that it technically violates the guidelines for μP operation, which for a 66.6-MHz clock specifies a 15-nsec period, plus or minus typically 250 psec of jitter. However, you can make a case that, if the spreading modulates the period by only 75 psec, sufficient guardband remains for random variations. In practice, experiments show center spreading to significantly reduce EMI radiation without degrading performance.

An alternative technique is down-spread modulation, in which you shift the carrier frequency down by half the modulation amount so that you center the modulated waveform on a new carrier. The peak of that modulation is at the original carrier. For example, you move a 66.6-MHz fundamental down by 0.5% if you select a 1% modulation. A 75-psec carrier modulation means that the fastest and slowest clock periods are 15 and 15.15 nsec, respectively. However, the average clock period is 15.075 nsec, which is 75 psec lower than the period of a 66.6-MHz clock, meaning that the average frequency is actually 66.3 MHz. The advantage of down spreading is that it ensures that your system does not exceed the maximum processor clock speed. However, the lower average clock speed also slightly decreases performance.

Modulation implementation

You can modulate fundamental carrier frequency in several ways. One way is to directly modulate the reference clock. However, a major drawback of this technique is that the rest of the system also uses the reference, and many of the components, such as a floppy-disk drive, need a steady clock. With this technique, you would corrupt any fixed-frequency clocks, and those fixed-clock components would not operate properly.

The one technique that provides the most accurate and predictable results for a main clock system is to modulate the input of the VCO in a PLL (Figure 3). This technique uses the reference clock as a control element and has counters that look for time events to determine the location of the modulation at specific times. When the circuit identifies these events, it modulates the PLL, feeding a control voltage to the VCO. Feedback from the phase detector indicates whether the clock is above or below the target frequency, and the circuit accordingly adjusts the current sources. With this technique, clocks requiring a fixed frequency are unmodulated, and those that cause major EMI problems, such as memory and CPU clocks, are modulated.

Results using spread-spectrum modulation

A wide-view spectrum plot for a 66.6-MHz clock from the fundamental frequency to the fifth harmonic shows the peak reductions you would achieve with a $\pm 0.5\%$ center-spread shift (Figure 4). A magnified spectrum plot for a 66.6-MHz clock shows the energy reduction with a 0.5% center-spread and a $\pm 0.5\%$ (0 to -1%) down-spread shift over an unmodulated signal (Figure 5).

Reviewing the discrete frequency for each cycle number across the normal spectrum of a 66.6-MHz clock (Figure 6), you can see the energy dispersion resulting from both a $\pm 0.5\%$ center-spread modulation and a $\pm 0.5\%$ (0 to -1%) down-spread modulation. As these timing waveforms illustrate, spread-spectrum techniques clearly meet the goal of decreasing EMI by smoothly changing clocks while dispersing energy most efficiently across a range of frequencies relative to the fundamental frequency. Using spread-spectrum techniques is viable to answer the growing need for EMI control.

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Authors' biographies

Steve Bolger is director of engineering at Integrated Circuit Systems (ICS, www.icst.com), where he has been employed for four years. His design work at ICS includes motherboard clock generators, a zero-delay buffer PLL, and Rambus clocks. Bolger received his BSEE at San Francisco State University (San Francisco) and his MSEE at Stanford University (Stanford, CA).

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